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OBSERVED ASSOCIATIONS BETWEEN THE SOLAR INTERIOR, CORONA, AND SOLAR WIND

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ABSTRACT

Using polarized brightness (pB) measurements made by the High Altitude Observatory (HAO) Mauna Loa Mk III K-coronameter, we investigate the daily changes of path-integrated density at 1.15 $R_\odot$. During 1996, when simultaneous pB and helioseismology data were available, we find that the correlation of pB (at zero time lag and 20° latitude lag) varies with latitude in the same way that the subsurface differential rotation inferred from helioseismology does. The association is such that bands of higher pB correlation are associated with retrograde subsurface rotation and that lower pB correlation bands are associated with prograde subsurface rotation. We also show that polar coronal holes are distinguished by a nonrecurring longitudinal structure as opposed to a recurring structure in the quiet Sun. In addition, the levels of pB and standard deviation σ_{pB} of pB are about half of those of the neighboring quiet Sun. These statistical characteristics of coronal density in polar holes and the quiet Sun were also present in 1993–1994 and are replicated in the statistics of the distant solar wind observed by *Ulysses*. The association of the density (pB) correlation with subsurface flow (when simultaneous data were available in 1996), together with the association of the latitudinal dependence of the statistical characteristics (average, standard deviation, and autocorrelation function) of the coronal (pB) and solar wind (*Ulysses*) density (when simultaneous data were available in 1993–1994), suggest a correlated variability of subsurface flow, coronal density, and solar wind density organized by solar latitude.

Subject headings: solar wind — Sun: corona — Sun: interior

1. INTRODUCTION

The growing number of ground- and space-based observations of the Sun (e.g., Hansen et al. 1969; Howard & LaBonte 1980; Hathaway et al. 1996; Kosovichev & Schou 1997; Schou et al. 1998) and of the heliosphere (e.g., Bame et al. 1992; McComas et al. 2000) has made it possible to explore associations between the corona, the solar interior, and interplanetary space. Such associations provide clues for identifying and understanding the physical processes by which magnetic fields generated in the solar interior make their way through the different layers of the solar atmosphere, shaping the solar wind flow and determining solar activity. Since the realization that the near-Sun path-integrated density profile is radially preserved in the corona except within streamers (Woo & Habbal 1999a, 1999b), coronal measurements nearest to the Sun have emerged as the key for relating the corona to the distant solar wind probed by interplanetary spacecraft (Woo & Habbal 2000; Habbal & Woo 2000). By virtue of their proximity to the Sun, these measurements are also the most likely to reveal associations with features of the solar interior. The purpose of this Letter is to show that the daily changes of path-integrated density observed in white-light measurements near the Sun appear to be related to helioseismology observations (§ 2) and to *Ulysses* measurements of the fast solar wind (§ 3). The implications of these results are discussed in § 4.

2. CORONA AND SOLAR INTERIOR

To explore the relationship between the corona and the solar interior, we choose the period of 1996 May 9–September 29 (day of year [DOY] 130–273) when the subsurface velocity flows were first measured (e.g., Kosovichev & Schou 1997; Schou et al. 1998; Birch & Kosovichev 1998) and for which there are simultaneous measurements of near-Sun density. For the latter, we use the polarized brightness (pB) measurements collected by the High Altitude Observatory (HAO) Mauna Loa Mk III K-coronameter (Fisher et al. 1981) as a proxy for the density at the point of closest approach to the Sun. The latitudinal variation of pB at a fixed radial distance of 1.15 $R_\odot$ is derived from measurements taken every 5° in latitude. A total of 107 daily east-limb profiles were available during this time period of which 19 representative examples are shown in gray in the upper plot of Figure 1*a*. The superposed black points forming a thick line are the average of the 107 profiles. As earlier studies have shown (Woo & Habbal 1999a, 1999b; Habbal & Woo 2000), density is lowest within the radial extension of the boundaries of the polar coronal hole (above ≈60° latitude) and rises by about a factor of 2 beyond these boundaries in what is known as the quiet Sun (latitudes ≈30°–60°). The profiles in Figure 1*a* show that there is nearly as much relative change in the density at a given latitude in the polar coronal hole as there is in the quiet Sun. This significant (factor of 2) variability is contrary to the previous conclusions that there is little change in the density of polar coronal holes (Guhathakurta & Holzer 1994). The latter result, however, was based on observations in the altitude range of 2.5–4.5 $R_\odot$, where the tenuous density in polar coronal holes is not detected by the Mk III K-coronameter (Woo & Habbal 1999b).

The lower plot of Figure 1*a* represents the latitudinal profile of the standard deviation σ_{pB} of pB at a fixed latitude and exhibits three peaks. The low-latitude peak (at ≈−10°) is associated with sunspot activity (Hansen et al. 1969). It is evident from the individual pB profiles in Figure 1*a* that the boundary of polar holes varies in latitude with time. Thus, σ_{pB} computed at constant latitude (as in Fig. 1*a*) will be artificially elevated near the average boundary of the hole (forming the two peaks

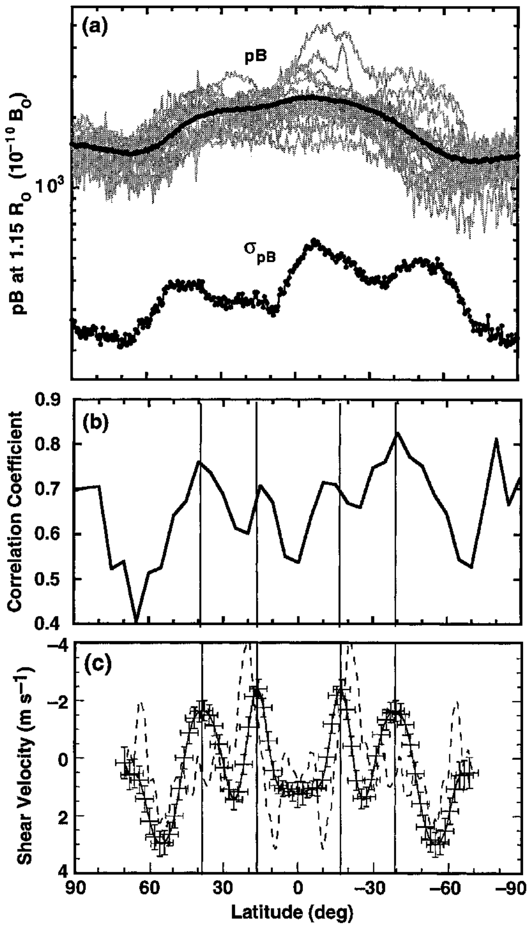

FIG. 1.—(*a*) Mk III east-limb measurements of pB as a function of latitude in 5° increments. The black points forming a thick line represent the averages of the 107 profiles covering the period 1996 May 9– September 29 (DOY 130–273). Nineteen of the 107 profiles are shown in gray. The standard deviation $\sigma_{\rm pB}$ of the 107 profiles is also shown. (*b*) Computed correlation coefficient of pB variations separated by 20° in latitude as a function of the midpoint latitude in increments of 5°. (*c*) Variations with latitude of the subsurface azimuthal velocity after subtraction of the differential rotation reproduced from Kosovichev & Schou (1997). The vertical lines in (*b*) and (*c*) are merely a guide to accentuate the similarity between the azimuthal velocity and the density correlation patterns.

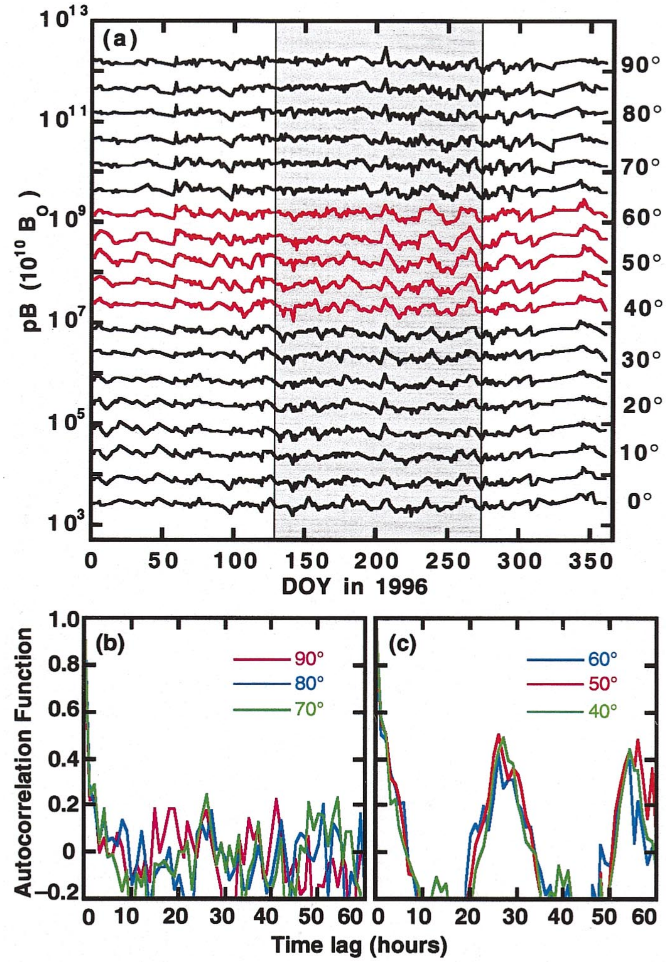

FIG. 2.—(*a*) Stack plot of Mk III east-limb pB time series in 1996 of the northern hemisphere in 5° increments. The pB time series are multiplied by factors of 3, 10, 30, 100, etc., as the latitude is increased from 0°. The shaded region corresponds to the period of 1996 May 9–September 29 (DOY 130–273). The time series in the latitude range of 40°–60° and corresponding approximately to the quiet-Sun region are shown in red. (*b*) Autocorrelation function of pB time series at latitudes 70°, 80°, and 90° during the DOY 130–273. (*c*) Same as (*b*), except latitudes are 60°, 50°, and 40°.

at $\approx \pm 50°$ latitude), and the peak in $\sigma_{\rm pB}$ will move with latitude as the average polar hole boundary changes with the solar cycle. The migration of such high-latitude peaks toward the poles from 1965 to 1967 noted by Hansen et al. (1969) can thus be largely explained by the shrinking of the polar coronal holes during the rising phase of the solar cycle (Harvey 1996). In addition to the factor of 2 difference in the levels of pB and $\sigma_{\rm pB}$ between polar coronal holes and the quiet Sun, another feature distinguishes these two regions. Shown in Figure 2*a* are the 1996 time series of the day-to-day variations of pB on the east limb of the northern hemisphere for latitudes ranging from 0° to 90° in 10° increments; the shaded period corresponds to DOY 130–273. As shown by the autocorrelation function (calculated by accounting for data gaps after a linear trend was removed from each time series) in Figure 2*b*, pB variations in the polar coronal hole do *not* recur at the solar rotation period but *do* in the quiet Sun. A striking feature of Figure 2*a* is the wide range of latitudes over which pB appears to be correlated. Similar correlations have been observed in magnetic field rotation rates (Gilman 1977). Reproduced in Figure 1*c* are the alternating zonal bands of slow (retrograde) and fast (prograde) rotation observed by Kosovichev & Schou (1997) in the solar interior after the differential rotation is subtracted; these are in turn closely related to the torsional oscillations of the Sun (Howard & LaBonte 1980; Hathaway et al. 1996). Schou et al. (1998) have presented evidence showing that this subsurface flow pattern may persist to a depth below the solar surface of perhaps as much as 0.05 $R_\odot$. Motivated by the ≈20° width of these flow bands, we computed and plotted in Figure 1*b* the correlation of pB at a constant time but between latitudes separated by 20° as a function of latitude. The density correlation variations in Figure 1*b* bear a close resemblance to the flow profile of Figure 1*c*. The four peaks in density correlation roughly correspond to the four minima in azimuthal flow (four minima in Fig. 1*c* since the flow axis is reversed), while the five minima in density correlation roughly correspond to the five peaks in azimuthal flow. The bands of high- and low-density correlation are, therefore, associated with those of slower and faster rotation, respectively. Additional evidence for this association is found in the coincidence of the anomalously slow subsurface polar rotation found by Schou et al.

(1998) and Birch & Kosovichev (1998), with the high-density correlation between latitudes separated by 20° observed at the poles at the same time (see Fig. 1*b*).

3. CORONA AND INTERPLANETARY SPACE

Since the *Ulysses*' polar passages did not take place during the helioseismology measurements of 1996, we cannot compare all three data sets (interior, corona, and solar wind) at the same time. Instead, we compare the longitudinal variations of coronal density (pB) with the longitudinal variations of solar wind density observed by the Solar Wind Observations Over the Poles of the Sun (SWOOPS) instrument on *Ulysses* (Bame et al. 1992) and show that the latitudinal dependence of the statistical behavior in these two quantities is similar. We investigate the slow rather than the fast scan measurements (McComas et al. 2000) because the longitudinal variations are less confused by latitudinal variations during the slow scan. To match the longitudinal resolution of the pB measurements, we use the daily proton density measurements. *Ulysses*' slow scan of the South Pole, which took place from 1993 September 26 (DOY 269) to 1994 September 14 (DOY 622 with respect to 1993), covered the latitude range of −40° to −90°. Shown in Figure 3*a* are the time series of pB covering this period. Following Figure 1*a*, but based only on east-limb measurements, we show a representative 19 of the 190 daily profiles (*light gray*) and the average of the 190 profiles (*thick line*) during DOY 269–622 in Figure 3*b*. The daily *Ulysses* proton density measurements and their 27 day running averages are displayed in Figure 3*f*. As found earlier (Habbal & Woo 2000), the average latitudinal profile of the *Ulysses* solar wind density is similar to that of pB with comparable peak-to-peak variations. That the *Ulysses* solar wind density and pB at 1.15 $R_\odot$ both vary by a factor of 2 within the polar coronal hole (latitudes above ≈−60°) suggests a close relationship between them. The latitudinal profile of $\sigma_{\rm pB}$ during DOY 269–622 is shown in Figure 3*c*, while the corresponding *Ulysses* density standard deviation σ_n, computed in a 108 day (corresponding to four solar rotations) wide sliding window, is shown in Figure 3*g*. In spite of the dynamic interaction as the solar wind evolves with heliocentric distance, there is a correspondence between the longitudinal variations of density in the corona and those in the solar wind. Like the pB variations, the solar wind density variations also peak near −60° latitude. Note from Figures 1*a* and 3*c* that the peak in $\sigma_{\rm pB}$ migrates ≈10° equatorward from 1993/1994 to 1996, consistent with the growth of polar coronal holes during the declining phase of the solar cycle (Harvey 1996). Since *Ulysses* observes the solar wind locally in space, the similarity of the profiles of pB and $\sigma_{\rm pB}$ to those of n and σ_n, respectively, reinforces the notion that path-integration effects do not significantly affect the latitudinal profiles of density and density fluctuations of the fast wind inferred from pB measurements. Since the 1993–1994 boundary between the quiet Sun and the south polar coronal hole occurs near latitude −62° and since *Ulysses* crossed this latitude on 1994 May 5 (DOY 490 in 1993), we divide the *Ulysses* density measurements into the following two periods: (1) DOY 267–490, when it was over the quiet Sun in the latitude range of −40° to −62°, and (2) DOY 490–621, when it was over the polar coronal hole at latitudes higher than −62°. The pB measurements corresponding to these polar coronal hole and quiet-Sun regions at the Sun are shaded in Figure 3*a*. The autocorrelation functions of pB in Figures 3*d* and 3*e* for latitudes −80 and −55° demonstrate that the presence of a recurring structure in the quiet Sun

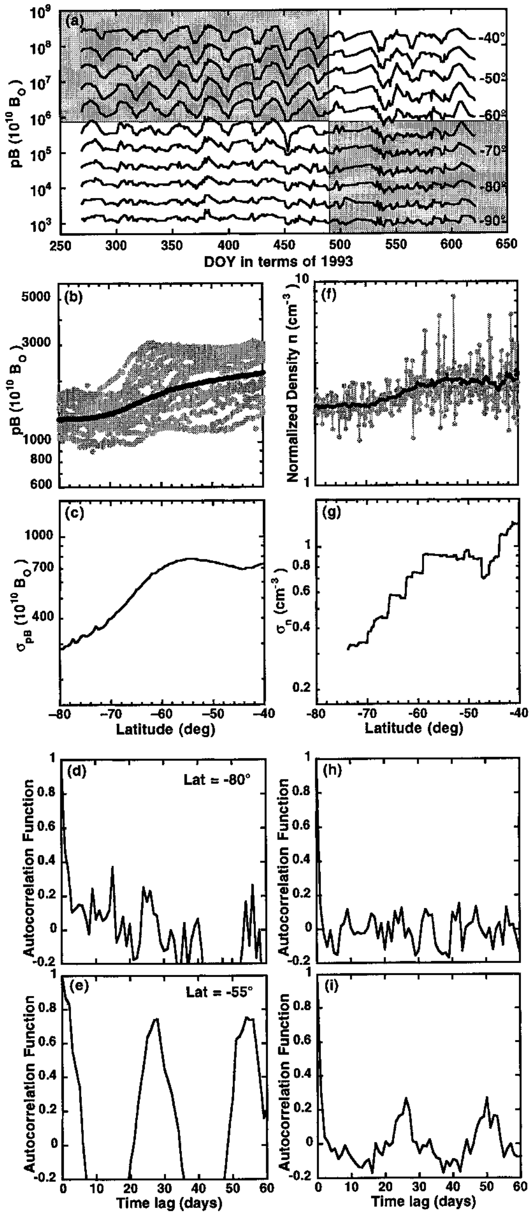

FIG. 3.—(*a*) Stack plot of Mk III east-limb pB time series of the southern hemisphere in 5° latitudinal increments between 1993 September 24 (DOY 267) and 1994 September 14 (DOY 622 in terms of 1993) when *Ulysses* also probed the southern hemisphere in the latitudinal range of −40° to −90°. The pB time series are multiplied by factors of 3, 10, 30, 100, etc., as the latitude is decreased from −90° to −40°. DOY 490 in terms of 1993 (1994 May 5) marks the date when *Ulysses* crossed the latitude of −62°. *Ulysses* probed lower latitudes before (*upper left-hand corner shaded region*) and higher latitudes after (*lower right-hand corner shaded region*). (*b*) The pB profile similar to that in Fig. 1*a*, but for the time period found in (*a*) (DOY 267–622). (*c*) The $\sigma_{\rm pB}$ profile similar to that in Fig. 1*a*, but for the time period found in (*a*) (DOY 267–622). (*d*) Autocorrelation function of pB time series at −80° latitude during DOY 490–621. (*e*) Same as (*d*), except at −55° latitude and during DOY 267–490. (*f*) *Ulysses* daily measurements as a function of latitude and the average computed with a 27 day sliding window and shown as black points. (*g*) Standard deviation of *Ulysses* daily density measurements as a function of latitude computed in a 108 day sliding window. (*h*) Autocorrelation function of *Ulysses* density measurements during DOY 490–621. (*i*) Same as (*h*), but during DOY 267–490.

and the absence of it in polar coronal holes were also observed in 1993–1994. The corresponding autocorrelation functions of the *Ulysses* density measurements show this same contrast between polar coronal holes (Fig. 3*h*) and the quiet Sun (Fig. 3*i*) in the distant solar wind, suggesting that the disappearance of solar rotation effects above $-60°$ latitude, first noted by Phillips et al. (1995) and Neugebauer et al. (1995), stems from the entrance of *Ulysses* into the radially extended polar coronal hole region. Since a recurring structure is absent in polar coronal holes, it is not possible to use a spectral analysis of the *Ulysses* measurements to trace low-latitude high-speed wind to polar coronal holes (Roberts & Goldstein 1998).

4. DISCUSSION AND CONCLUSIONS

From the simultaneous observations in 1996 of pB and helioseismology, we have demonstrated that the correlation of coronal density variations between latitudes separated by 20° shows a correspondence with the subsurface zonal variations of the Sun's differential rotation. From equator to pole, bands of high- and low-density correlation appear to be associated with those of retrograde and prograde rotation, respectively. The correlation between flow speed and density may not be surprising since the flow bands are thought to generate the magnetic field, and density and magnetic field are closely related in the solar corona. However, the physical meaning of the correlation is not yet understood.

The profiles of Figures 1*b* and 1*c* represent the first direct association between the corona and the Sun's velocity flow. Like torsional oscillations based on Doppler (Howard & LaBonte 1980) and magnetic field measurements (Snodgrass 1991), the density correlation bands are subtle and do not depend on the identification of coronal features. However, the alternating high-latitude flow bands and their relationship to the density correlation can be identified with coronal features. The slower bands appear to be associated with the polar coronal hole and the quiet Sun, within which the longitudinal structure is highly correlated. On the other hand, the intervening faster band appears to be associated with the coronal hole boundary, across which there is a steep density gradient and across which the longitudinal structure decorrelates as it changes from a nonrecurring to a recurring structure.

Although Hansen et al. (1969) noted that $\sigma_{\rm pB}$ appeared to be organized in discrete latitude bands that were obscured in the latitudinal profiles of pB, neither profiles of $\sigma_{\rm pB}$ nor pB show any hint of an association with the bands of azimuthal flow (compare Figs. 1*a* and 1*c*). However, in the same way that patterns of several solar phenomena have suggested an indirect association with torsional oscillations through an extended solar cycle model (Wilson et al. 1988; Altrock 1997), the equatorward migration of the high-latitude peaks in the $\sigma_{\rm pB}$ profile during the declining phase of the solar cycle suggests the same association. The measurements of pB complement helioseismic measurements in two important ways. First, unlike solar and helioseismic measurements, there is essentially no degradation in the Mk III pB measurements near the poles at 1.15 $R_\odot$; thus, the density correlation observes polar regions more reliably. Second, the extensive database of Mk III white-light measurements makes it possible to investigate the solar cycle dependence of the density correlation and the subsurface flow. We have also shown that polar coronal holes are distinguished by levels of pB and $\sigma_{\rm pB}$ that are half of those of the neighboring quiet Sun and by nonrecurring longitudinal structure as opposed to recurring structure in the quiet Sun. These statistical characteristics of coronal density in the polar holes and in the quiet Sun are also present in 1993–1994 and are replicated in the distant solar wind observed by *Ulysses*. The comparisons between the white-light and the *Ulysses* measurements are the first to be based on pB measurements at 1.15 $R_\odot$. Besides being closer to the Sun, these measurements have a significantly higher signal-to-noise ratio than those at a higher altitude (Woo & Habbal 1999b). With this higher sensitivity, latitudinal and longitudinal variations even in the tenuous polar regions of the corona are detected, making it possible to compare high-latitude white-light and in situ solar wind measurements using a quantitative and systematic approach (as shown in Fig. 3) not available in earlier comparisons (Gosling et al. 1995; McComas et al. 2000). The association of density (pB) correlation with subsurface flow (when simultaneous data were available in 1996), together with the association of the statistical characteristics (average, standard deviation, and autocorrelation function) of coronal (pB) and solar wind (*Ulysses*) density (when simultaneous data were available in 1993–1994), suggests correlated variability of subsurface flow, coronal density, and solar wind density organized by solar latitude.

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